

**Annual Project Summary
Maintenance, Data Archive and Analysis
of existing low- frequency GTSM Installations in California.
NEHRP Grant 04-HQ-AG-0116**

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seismology, geodesy, borehole geophysics

Project Objectives and Approach

This proposal enables a program of **maintenance and analysis of now six deep borehole Gladwin Tensor Strainmeters (GTSM)** in California for a bridging period of three years to ensure continuity of observations into the early PBO era. These sites, (PFT (1983), SJT (1983), CLT (1996), DLT (1986), FLT (1986) and CHT (1992)) operate at a sensitivity of better than 10^{-9} , with data sampling at 30 minute intervals. They continue to provide the NEHRP program with a *unique* tensor strain data base which needs to be maintained at least until key PBO arrays are established to ensure continuity of these long term data sets which continue to produce significant insight on fault motion. The project provides open access to quality assured data archive, identification of strain events and anomalies, correlation with datasets from other instrumentation, and maintenance of all pre-PBO GTS sites

Archived long term baseline data are openly available from <http://www.cat.csiro.au/dem/msg/straincal/straincal.html> for 6 months to July 1 2005, and also from http://www.gtsmtechnologies.com/NEHRP/strain_download/strain_form.html from December 2004 onwards. Data are also provided in near real time in the USGS Menlo Park computer system (***thecove:/home/mick/QUICKCHECK***). These data permit real time monitoring for short term strain phenomena.

The **immediate objectives** of the project are

- Provision of data for understanding of stress accumulation and relief processes, and aseismic fault interactions.
- Operation and Maintenance of six instruments in California to continue the 20 year-long baseline of data.
- Detailed editing and archive maintenance of a permanent archive of instrument data at Berkeley, Menlo Park, and in on line user-friendly form.
- Ongoing analysis of continuous unique low frequency shear strain data, identification and modeling of significant strain events, and publication as appropriate of modeling studies based on the constraints of these data.
- Near-real time alert response as part of the Parkfield Prediction experiment.

Archived Data

Archived data have been moved to our production facility from Dec 2004 onwards. The CSIRO archive will remain on line for a further 6 months only. Thereafter the archive will be maintained only at GTSM for download from

http://www.gtsmtechnologies.com/strain_download/strain_form.html.

- **Parkfield**

Long term data plots are shown below.

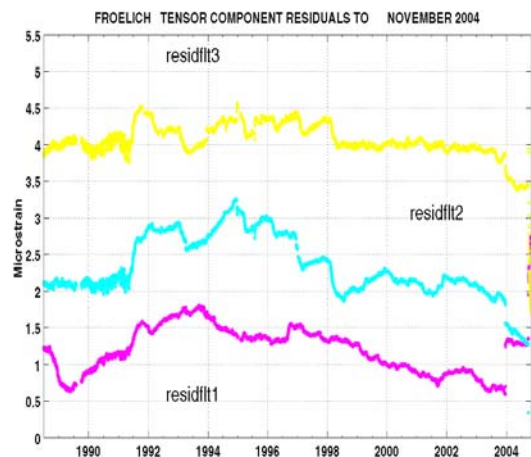
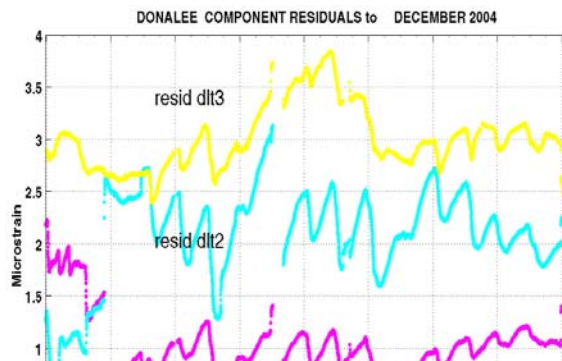
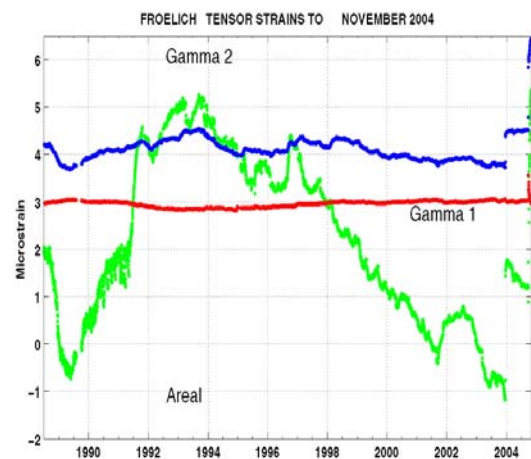
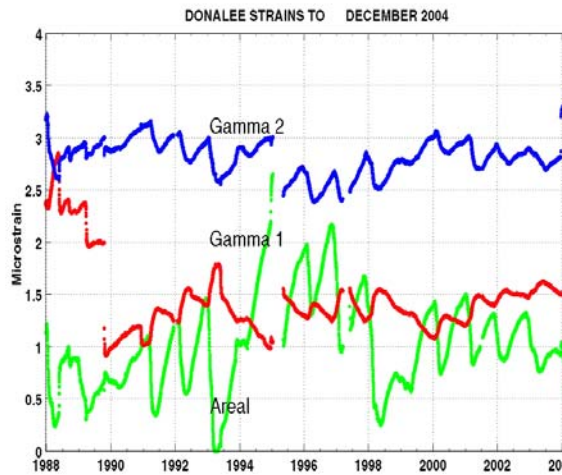


Figure 1(a): Long term tidally calibrated residual strain data from DonnaLee site at Parkfield to November 30, 2004.

Figure 1(b): Long term tidally calibrated residual strain data from Frohlich site at Parkfield to November 30 2004.

For each plot, the lower panel contains residual component data from which the effects of the disturbance caused by drilling on the virgin strain field have been removed.

The major steps at **DLT** are for the Loma Prieta in 1989, the M4.9 at Parkfield in December 1994, San Simeon in December 2003, and the recent M6 at Parkfield of September 28,2004.

The major steps at **FLT** are also for Loma Prieta, San Simeon, and Parkfield M6, September 28,2004.

Note that the gauge residuals have a Y axis scale range of ± 4 microstrain for each component, and show that excluding known tectonic events, the average variation from the mean in gauge strain rates has been less than **± 0.3 microstrain per year for the whole of the 18 year record,(1986-2004).**

Since May 2003, FLT channel 2 data has required considerable editing to eliminate noise particularly in the hotter months of the year. The temperatures in the site cabinet at FLT regularly run at between 45 and 62 degC during the summer.

- **San Juan Bautista and Chabot**

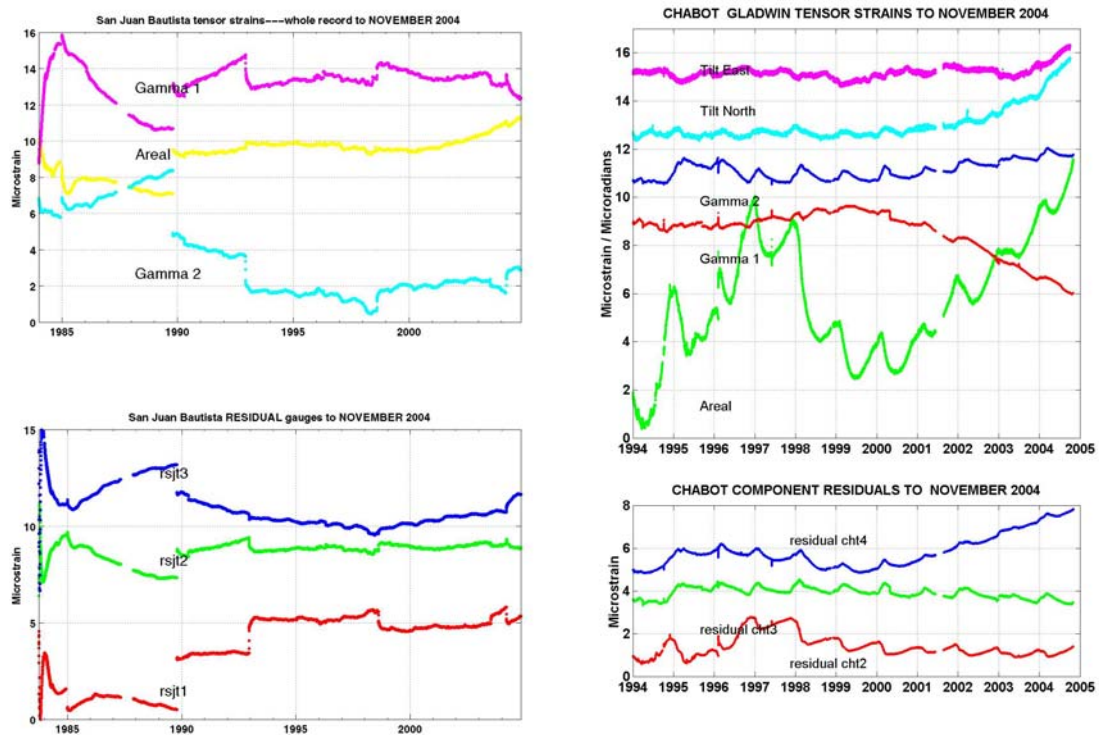


Figure 2(a): Long term tidally calibrated residual strain data from San Juan Bautista site to November 30 2004.

Figure 2(b): Long term a priori calibrated residual strain and tilt data from Chabot site in San Francisco Bay Area to November 30,2004.

For **SJT**, the major steps are for the Chittenden eq. of 1984, the Loma Prieta of 1989, slow earthquakes of 1992, 1996, 1998, 2003 and 2004.

Note that the gauge residuals have a Y axis scale range of ± 4 microstrain for each component, and show that excluding known tectonic events, the average variation in gauge strain rates has been less than **± 0.6 microstrain per year for the whole of the 21 year record (1983-2004).**

For **CHT**, the major signal in the data to mid 2000 correlates with the San Leandro reservoir levels to which this site is particularly topographically exposed (**Figure 3**). The variation in the CHT site is annual and is directly related to the exposure of the site to the varying water storage in nearby Lake Chabot, and is seen on all these borehole instruments in this array.

Since then there have been accumulating strain rate and tilt rate changes (which have accelerated in the tilt since 2003).

Note that the gauge residuals have a Y axis scale range of ± 4 microstrain for each component, and show that excluding known tectonic events, the average variation in gauge strain rates have been less than **± 0.5 microstrain per year for the whole of the 12 year record,(1992 – 2004).**

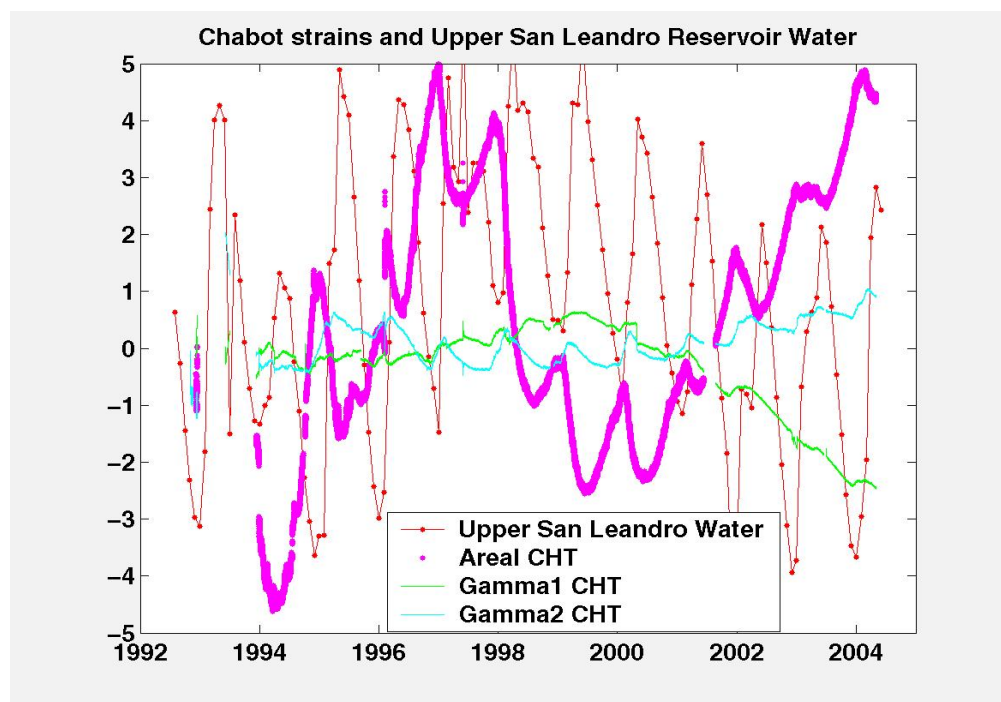


Figure 3. Chabot Strains and San Leandro water levels .

- **Southern California**

Coldbrook

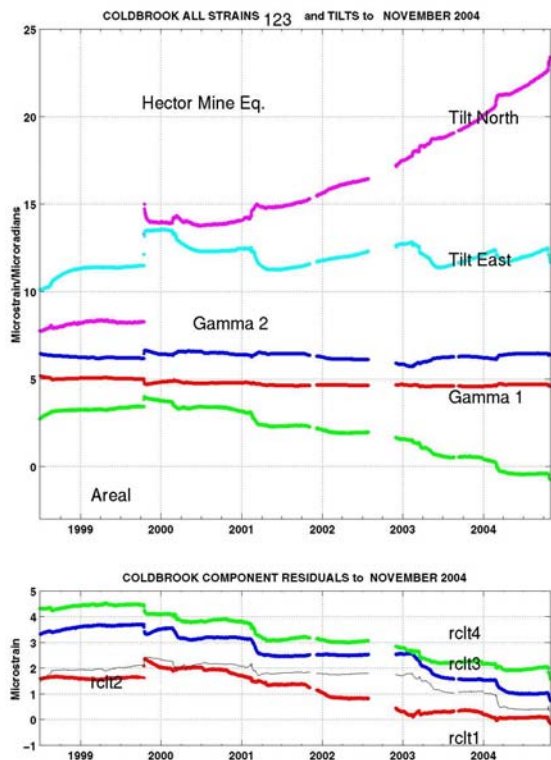


Figure 3(a): Long term data from Coldbrook with a priori residual strains calculated from component channels 1, 2 and 3.

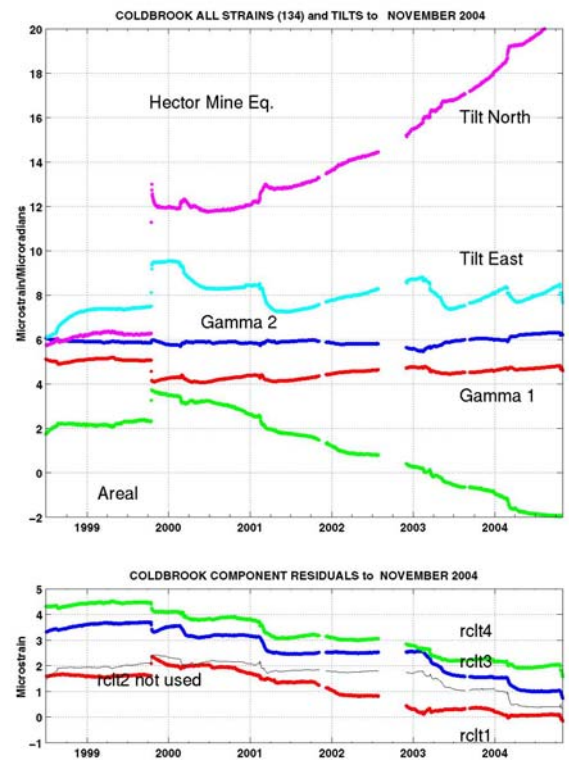


Figure 3(b): Long term data from Coldbrook with a priori calibrated residual strain data calculated from component channels 1, 3 and 4

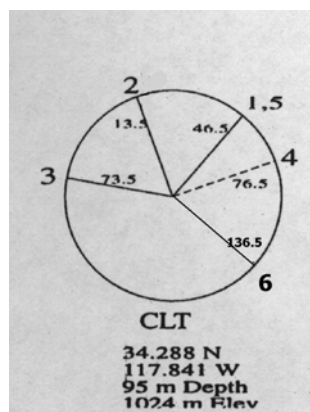


Figure 3(c): gives component angles for Coldbrook.

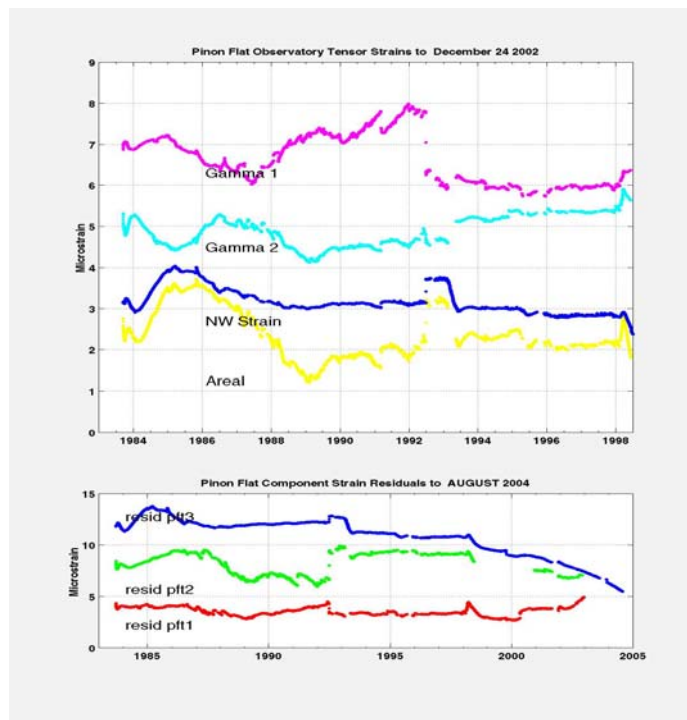
For **CLT**, the major step is the Hector Mine Eq. of 1999.

Note that the gauge residuals have a Y axis scale range of ± 4 microstrain for each component, and show that excluding known tectonic events, and a large local transient offset measured on all strain and tilt channels late in the 1998 rain season, the average variation in gauge strain rates has been less than ± 0.2 microstrain per year over the 8 year record (1996-2004).

Pinon Flat

For **PFT**, the major step in the data is the Landers Eq of 1992

Figure 4: Long term residual strain data from Pinon Flat site in Southern California to Mid 1998, and in the lower panel, residual component data to September 2004.



Note that the gauge residuals have a Y axis scale range of ± 4 microstrain for each component, and show that excluding known tectonic events, average variation in gauge strain rates has been less than **± 0.1 microstrain per year for the whole of the 18 year record (1986-2004).**

During September 2004, several restarts of the DCP transmitter were required, and the site was taken off line until this problem can be remedied, probably during the PBO deployment field trip in early 2005.

Measurements of Coseismic strain offsets and Recovery processes associated with the Parkfield event of September 28, 2004

The Parkfield M6 earthquake of September 28, 2004 is the major co-seismic offset in the Parkfield sites data streams.

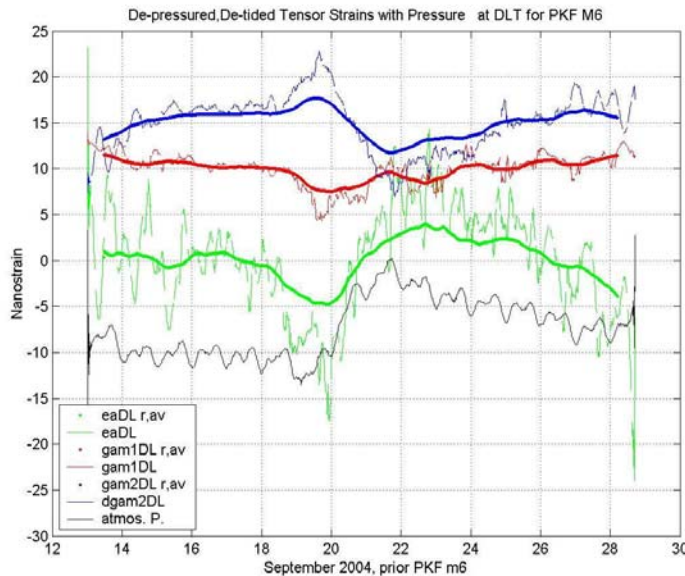


Figure 5: Detided, depressured residual strain data **from DLT** is plotted with the atmospheric pressure record, including a running mean of the strains.

The pressure admittance for this site has been measured previously at less than $0.5\text{n}\epsilon$ per mbar.

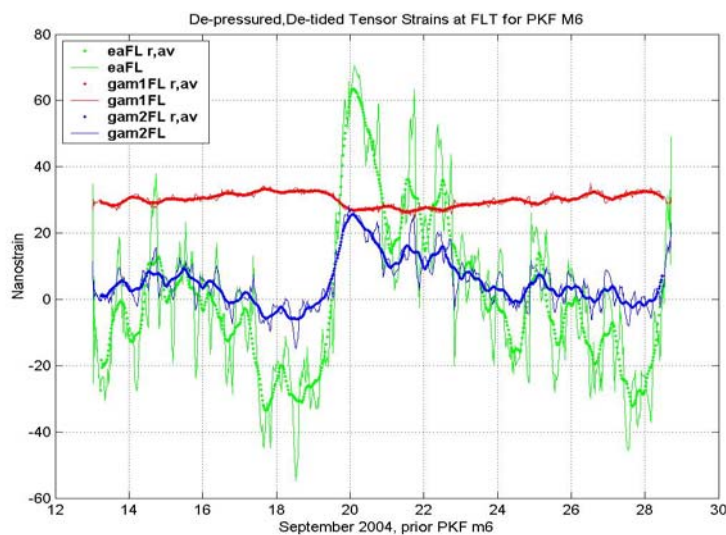


Figure 6: Detided, depressured residual strain data **from FLT** is plotted including a running mean of each of the strains.

In the FLT data, there is clear indication of a runaway some 5 to 6 hours before the event, but the major signal is 9 days prior when a high pressure system traversed the PKF area. There was no pressure change during the five to six hours before the event and the association of the anomaly shown below with the M6 event is ongoing. Effects prior to the event were evident on four of the six components at DLT and FLT. The data for the last two days before the earthquake is shown in figure 7 together with running means excluding the possible anomaly interval of a five to six hours.

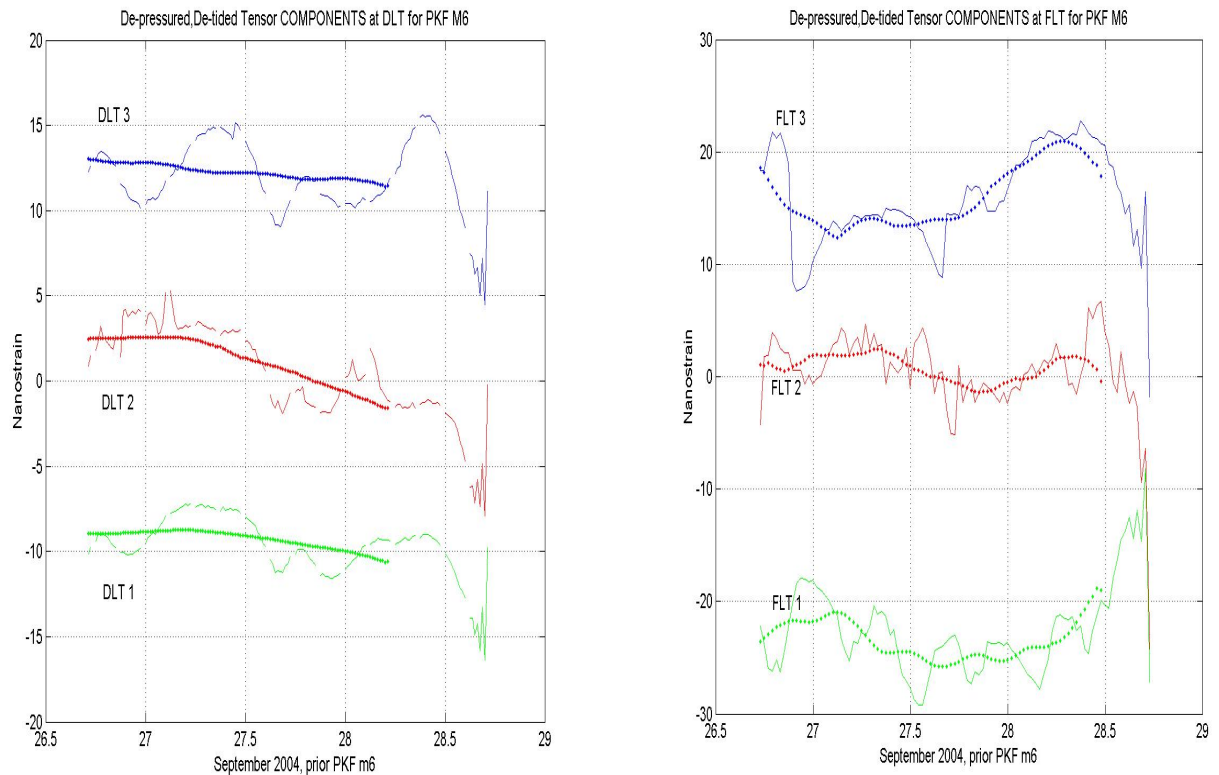


Figure 7(a) DLT, and **7(b)** FLT, show the component data 2 days data prior the M6 At PKF.

There was no atmospheric pressure anomaly on the 28 September.

Coseismic offsets for the Parkfield event were:-

	coseismic	Total post seismic from 0410281751 to 0410040233
eadl	1.8ue	1.0 ue
gam1dl	-330ne	-1.25ue
gam2dl	-450ne	-0.325ue
		from 0410281740 to 0410040233
eafl	-1.55ue	+3.8ue
gam1fl	+860ne	-700ne
gam2fl	+1.06ne	+470ne

The choice of times for the post seismic effects associates with the actual sample times at each site. The post seismic events are quite large relative to the co seismic. At DLT -**Figure 8(a)**, the post-seismic effects had the same sense as the seismic. At FLT -**Figure 8(b)**, reversals are indicated.

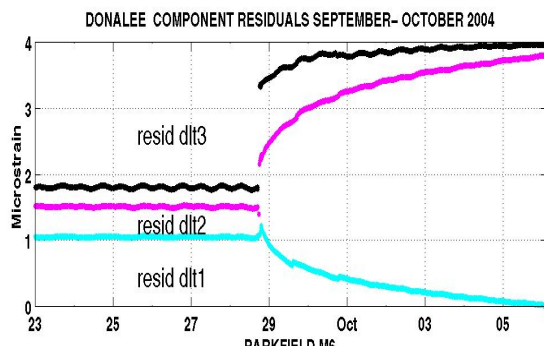
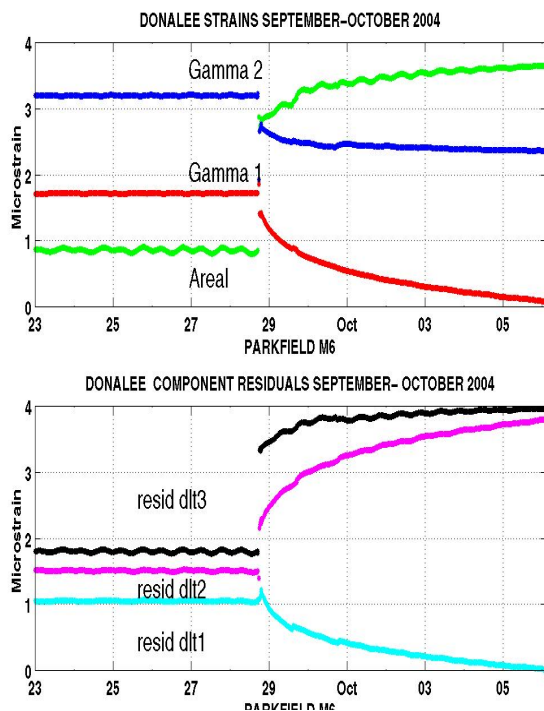


Figure 8(a): Immediate post seismic strains in upper panel, residual components in lower panel at DLT for PKF M6 Sept.28, 2004

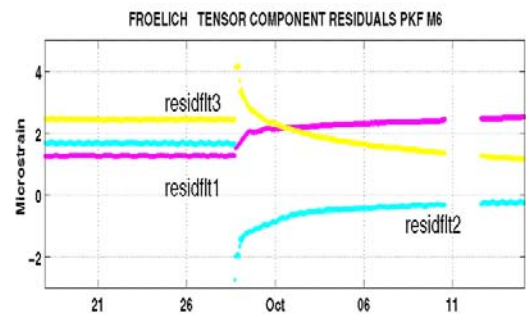
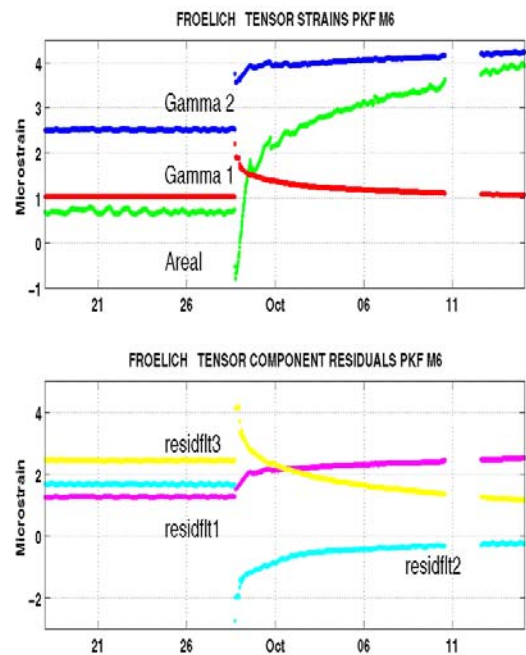


Figure 8(b): Immediate post seismic strains in upper panel, residual components in lower panel at FLT for PKF M6, Sept.28, 2004.

The post seismic effects over a more extended period than shown above were also modeled for each strain component as observed using the first 63 days of data at each site (See **Figure 9, 10, 11** below). The purpose of this analysis was to examine the commonality of recovery response at the two sites, which have quite different site characteristics. DLT site has a strongly recurring annual aquifer response obvious in its data whereas FLT has no equivalent, and it was expected that this would have some impact on the near fault region strain recovery process.

The results are presented in some detail below because the response is evidently not simple. The post seismic period was well modeled by least squares fitting of exponentials to the data. On each of the following figures, the upper plot shows daily averages of the actual data, and the numbers refer in left to right order to a) an arbitrary offset, b) The amplitude (in microstrain) of a best fit short term exponential, c) the time constant of this exponential in days, d) the amplitude of the identified long term exponential, e) its time constant (also in days), and f) a linear slope in nanostrain per day identified in the fit.

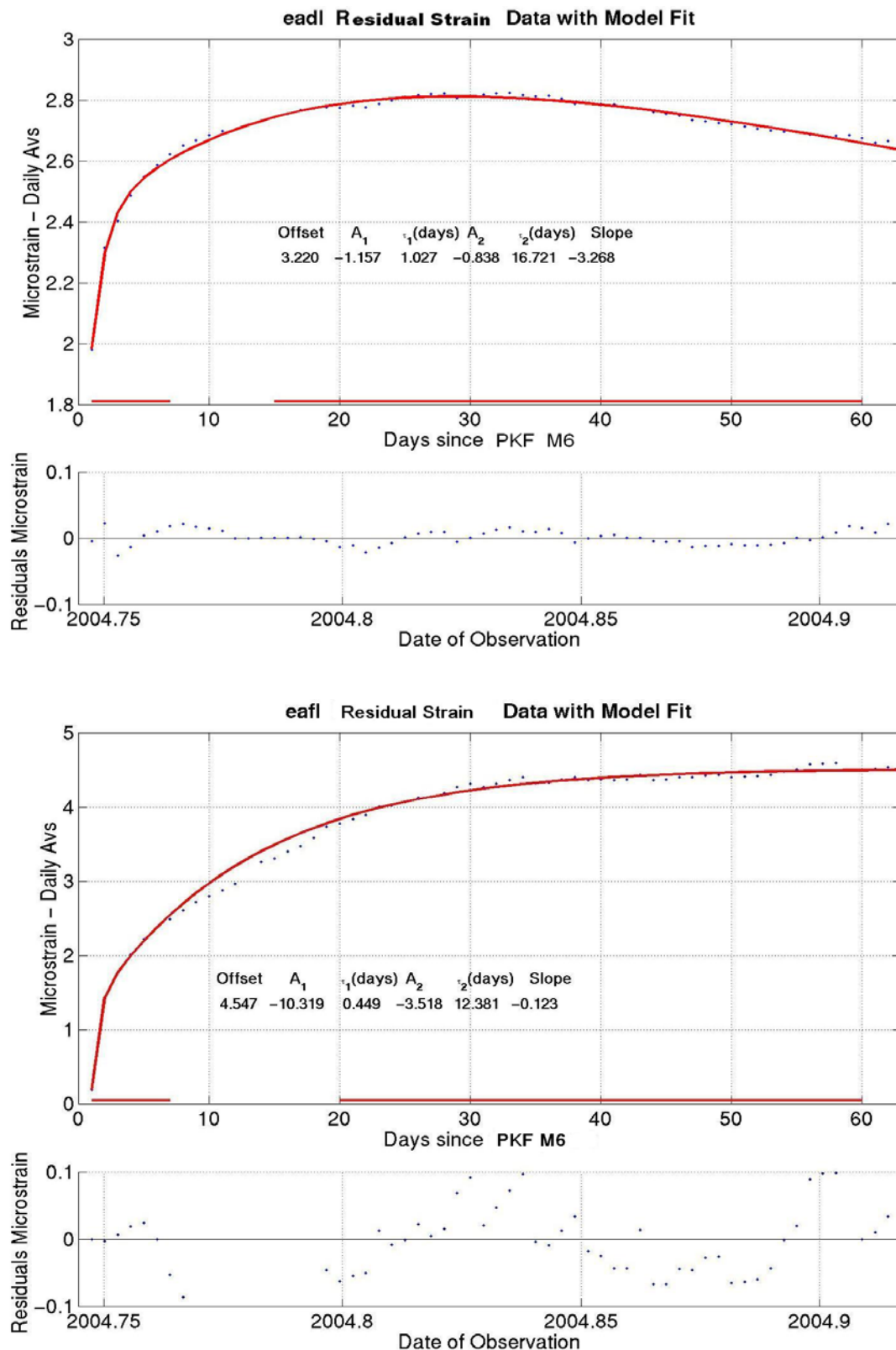


Figure 9: Double exponential modeled areal strain at DLT (top) and FLT for the 63 days following the event. The longer exponential time constants (16.72 and 12.38 days) are more comparable than the shorter ones (1.15 and 0.449 days) and are probably associated with more regional recovery processes. The shorter time constants are probably strongly controlled by fluid migration effects. Residuals are better than 0.1 $\mu\epsilon$

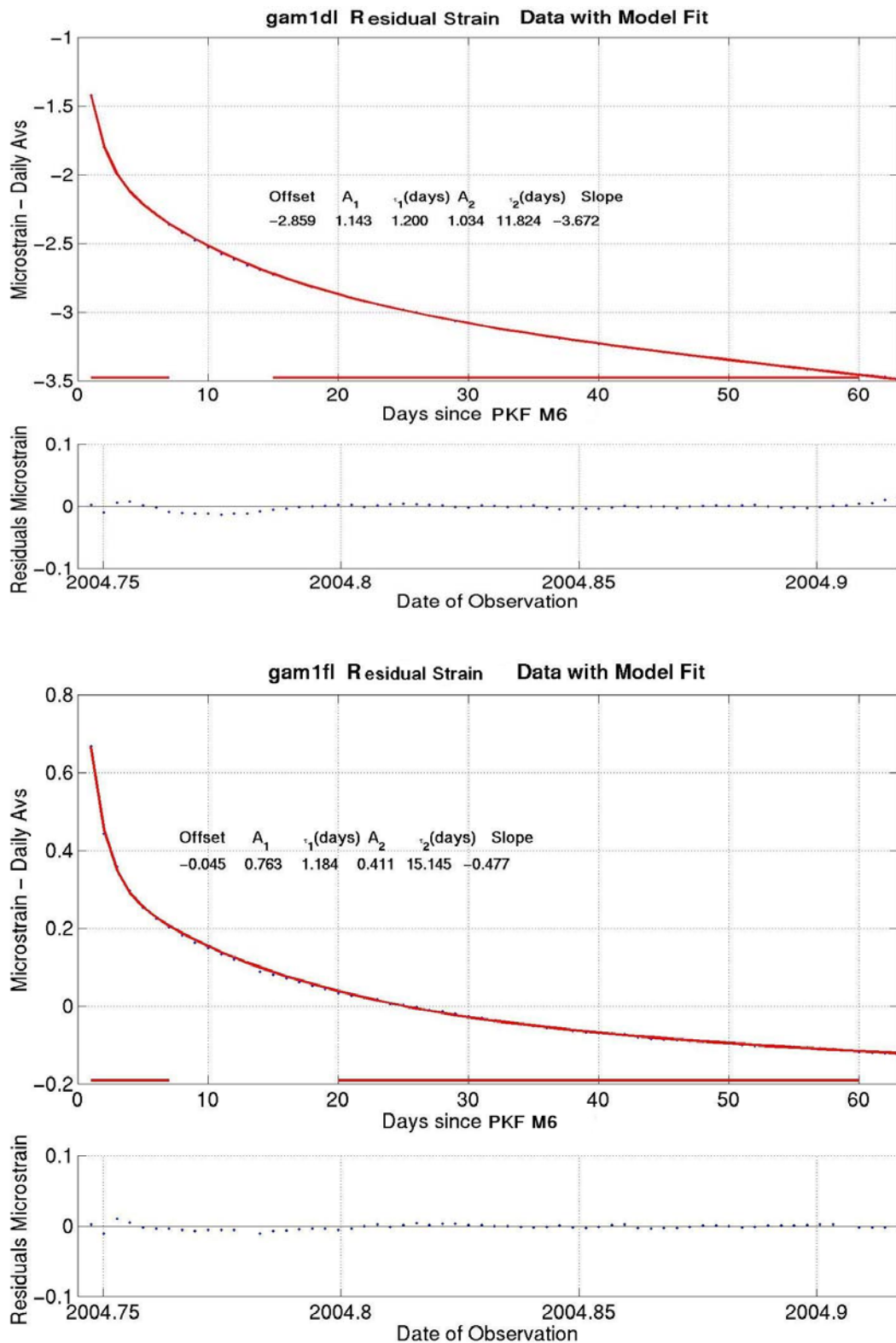


Figure 10: Double exponential modeled Γ_1 strain at DLT (top) and FLT (bottom) for the 63 days following the event. Both the longer exponential time constants (11.83 and 15.15 days) and the shorter ones (1.14 and 1.18 days) are comparable. There is no fluid effect expected in the shear and the values probably indicate two different scales of recovery process. Residuals are better than $0.02 \text{ n}\epsilon$ for the full period.

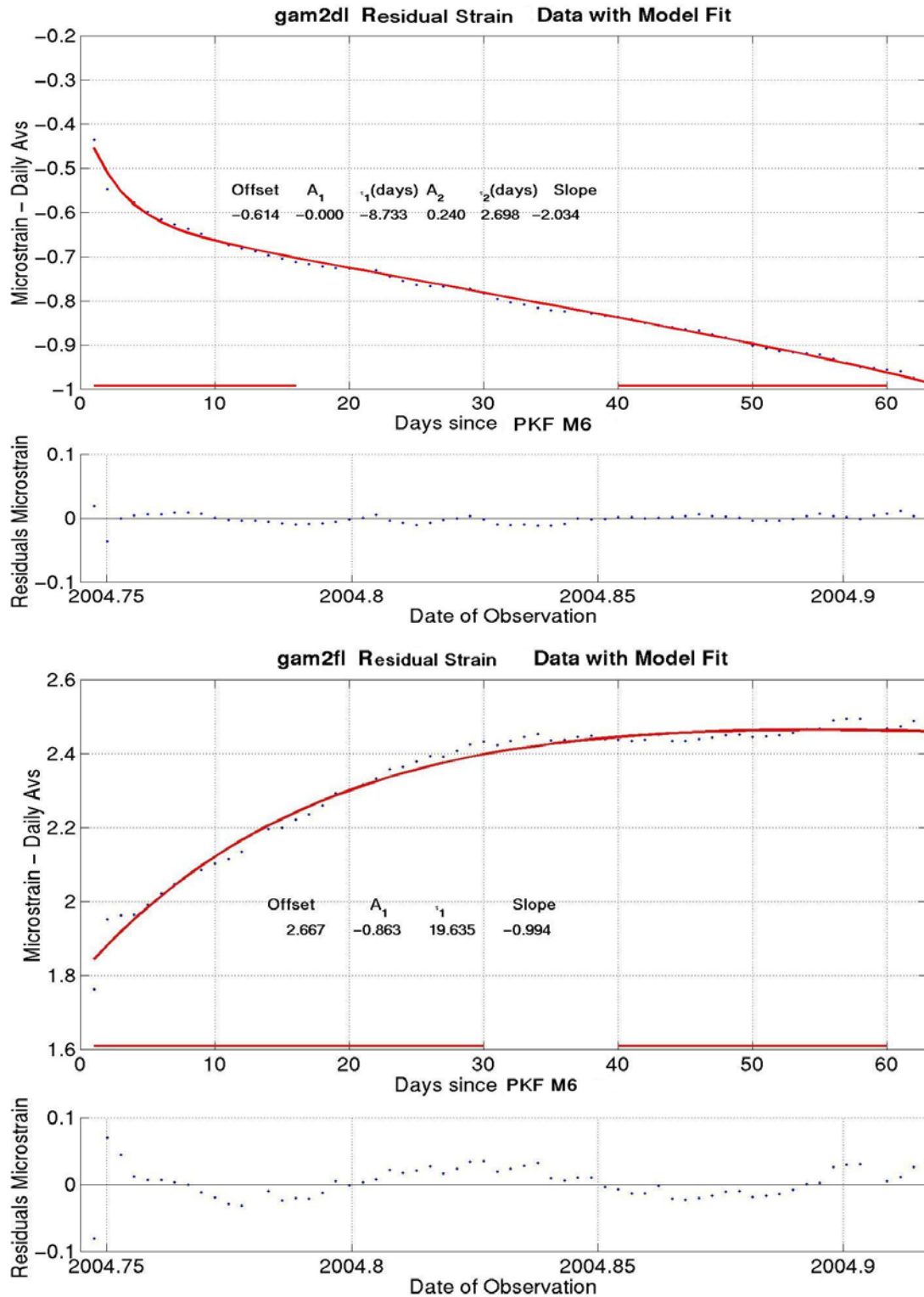


Figure 11: Modeled Γ_2 strain at DLT (top) and FLT (bottom) for the 63 days following the event. The DLT data are totally dominated by a linear term of approximately $2 \text{ n}\epsilon$ per day while the FLT data allowed only a single exponential with time constant 19.6 days to be isolated. We have not identified a reasonable explanation of these G_2 data differences. We expect subsequent data to resolve this issue.

Data Product Availability

Archived strain data from the Californian sites are stored in both raw component form, and as processed areal and shear strains. A regularly updated archive of data has been maintained in the USGS Menlo Park computer system since 1988. This data is stored in binary files with appended header information (USGS "bottle" format).

Until June 2005 the CSIRO page for direct access to data from all borehole tensor strain instruments in open format is <http://www.cat.csiro.au/dem/msg/straincal/straincal.html>
This page includes facilities for download of raw or processed data from our primary archive.

From December 2004, this same download facility will be available from http://www.gtsmtechnologies.com/NEHRP/strain_download/strain_form.html and

Automatically processed near-real time data is always available in *thecove:/home/mick/QUICKCHECK* for users with access to USGS plotting software "xqp", and via the USGS crustal deformation web pages in graphical form.

Scientists requiring other access to the archived data should contact Dr. M.T. Gladwin (+617 3376 4848, email mike@gtsmtechnologies.com or marie@gtsmtechnologies.com

Publications

Recent Publications

Gladwin M.T., & Malin P.E. Tensor Strain Seismograms: a New Tool for Earthquake Science. *EOS.(Trans. Am. Geo. Un.)*, 2004

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Steidl, J., Gladwin, M.T., Gwyther, R.L., & Vernon, F., Fault Processes on the Anza section of the San Jacinto Fault, *Proc. 2nd Plate Boundary Observatory Workshop*, 2.70-2.74, 2000

Agnew, D., Wyatt, F., & Gladwin, M.T., Strainmeter Calibration, *Proc. 2nd Plate Boundary Observatory Workshop*, I1-I5, 2000

Langbein, J., Roeloffs, E., Gladwin, M.T., & Gwyther, R.L., Creepmeters on the San Andreas Fault System between San Francisco Bay and Parkfield, *Proc. 2nd Plate Boundary Observatory Workshop*, 2.40-2.44, 2000

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Gladwin, M.T., Gwyther, R.L., Hart, R.H.G. and Breckenridge K. (1993) Measurements of the strain field associated with episodic creep events on the San Andreas fault at San Juan Bautista, California (1994). *J. Geophys. Res.* Vol 99 (B3), 4559-4565.

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Gwyther R.L., Gladwin M.T. and Hart R.H.G. (1992) A Shear Strain Anomaly Following the Loma Prieta Earthquake. *Nature* Vol 356 No.6365 pp 142-144.

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Gladwin, M. T., High Precision multi component borehole deformation monitoring. *Rev.Sci.Instrum.*, 55 , 2011-2016, 1984.

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Non-Technical Summary

Maintenance, Data Archive and Analysis of existing low frequency GTSM Installations in California

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II

seismology, geodesy, borehole geophysics

This project provides borehole observations of horizontal strain changes over timescales from minutes to years, which are critical to an understanding of fault processes associated with earthquakes along the San Andreas and San Gabriel / Sierra Madre fault systems. The project continues a program of maintenance and analysis of deep borehole tensor strain instrumentation initiated at Pinon Flat and San Juan Bautista in late 1983, at Parkfield in late 1986, at San Francisco East Bay in 1992, and a further deployment in the San Gabriel mountains region (Coldbrook) in 1996.

The project is intended to bridge these historic data sets into the new PBO program to be installed over the next few years. Continuous high precision and high resolution borehole tensor strain data provide an essential complement to long baseline interferometry studies (limited to sampling intervals of weeks), GPS studies, and seismic characterisation of faults. A major feature of this report is the inclusion of data from the M6 Sept 28, 2004 Parkfield event which was reported at Fall AGU, December 2004. These data are currently under close investigation, since they may suggest the existence (even for a magnitude 6 event) of short term precursor deformation in the last few hours before the event.

New data on the post seismic recovery processes have also been identified.